

# Lecture Notes in Physics

## Editorial Board

H. Araki, Kyoto, Japan  
R. Beig, Vienna, Austria  
J. Ehlers, Potsdam, Germany  
U. Frisch, Nice, France  
K. Hepp, Zürich, Switzerland  
R. L. Jaffe, Cambridge, MA, USA  
R. Kippenhahn, Göttingen, Germany  
H. A. Weidenmüller, Heidelberg, Germany  
J. Wess, München, Germany  
J. Zittartz, Köln, Germany

## Managing Editor

W. Beiglböck  
Assisted by Mrs. Sabine Lehr  
c/o Springer-Verlag, Physics Editorial Department II  
Tiergartenstrasse 17, D-69121 Heidelberg, Germany

**Springer**

*Berlin*  
*Heidelberg*  
*New York*  
*Barcelona*  
*Budapest*  
*Hong Kong*  
*London*  
*Milan*  
*Paris*  
*Santa Clara*  
*Singapore*  
*Tokyo*

## The Editorial Policy for Proceedings

The series Lecture Notes in Physics reports new developments in physical research and teaching – quickly, informally, and at a high level. The proceedings to be considered for publication in this series should be limited to only a few areas of research, and these should be closely related to each other. The contributions should be of a high standard and should avoid lengthy redraftings of papers already published or about to be published elsewhere. As a whole, the proceedings should aim for a balanced presentation of the theme of the conference including a description of the techniques used and enough motivation for a broad readership. It should not be assumed that the published proceedings must reflect the conference in its entirety. (A listing or abstracts of papers presented at the meeting but not included in the proceedings could be added as an appendix.)

When applying for publication in the series Lecture Notes in Physics the volume's editor(s) should submit sufficient material to enable the series editors and their referees to make a fairly accurate evaluation (e.g. a complete list of speakers and titles of papers to be presented and abstracts). If, based on this information, the proceedings are (tentatively) accepted, the volume's editor(s), whose name(s) will appear on the title pages, should select the papers suitable for publication and have them refereed (as for a journal) when appropriate. As a rule discussions will not be accepted. The series editors and Springer-Verlag will normally not interfere with the detailed editing except in fairly obvious cases or on technical matters.

Final acceptance is expressed by the series editor in charge, in consultation with Springer-Verlag only after receiving the complete manuscript. It might help to send a copy of the authors' manuscripts in advance to the editor in charge to discuss possible revisions with him. As a general rule, the series editor will confirm his tentative acceptance if the final manuscript corresponds to the original concept discussed, if the quality of the contribution meets the requirements of the series, and if the final size of the manuscript does not greatly exceed the number of pages originally agreed upon. The manuscript should be forwarded to Springer-Verlag shortly after the meeting. In cases of extreme delay (more than six months after the conference) the series editors will check once more the timeliness of the papers. Therefore, the volume's editor(s) should establish strict deadlines, or collect the articles during the conference and have them revised on the spot. If a delay is unavoidable, one should encourage the authors to update their contributions if appropriate. The editors of proceedings are strongly advised to inform contributors about these points at an early stage.

The final manuscript should contain a table of contents and an informative introduction accessible also to readers not particularly familiar with the topic of the conference. The contributions should be in English. The volume's editor(s) should check the contributions for the correct use of language. At Springer-Verlag only the prefaces will be checked by a copy-editor for language and style. Grave linguistic or technical shortcomings may lead to the rejection of contributions by the series editors. A conference report should not exceed a total of 500 pages. Keeping the size within this bound should be achieved by a stricter selection of articles and not by imposing an upper limit to the length of the individual papers. Editors receive jointly 30 complimentary copies of their book. They are entitled to purchase further copies of their book at a reduced rate. As a rule no reprints of individual contributions can be supplied. No royalty is paid on Lecture Notes in Physics volumes. Commitment to publish is made by letter of interest rather than by signing a formal contract. Springer-Verlag secures the copyright for each volume.

## The Production Process

The books are hardbound, and the publisher will select quality paper appropriate to the needs of the author(s). Publication time is about ten weeks. More than twenty years of experience guarantee authors the best possible service. To reach the goal of rapid publication at a low price the technique of photographic reproduction from a camera-ready manuscript was chosen. This process shifts the main responsibility for the technical quality considerably from the publisher to the authors. We therefore urge all authors and editors of proceedings to observe very carefully the essentials for the preparation of camera-ready manuscripts, which we will supply on request. This applies especially to the quality of figures and halftones submitted for publication. In addition, it might be useful to look at some of the volumes already published. As a special service, we offer free of charge L<sup>A</sup>T<sub>E</sub>X and T<sub>E</sub>X macro packages to format the text according to Springer-Verlag's quality requirements. We strongly recommend that you make use of this offer, since the result will be a book of considerably improved technical quality. To avoid mistakes and time-consuming correspondence during the production period the conference editors should request special instructions from the publisher well before the beginning of the conference. Manuscripts not meeting the technical standard of the series will have to be returned for improvement.

For further information please contact Springer-Verlag, Physics Editorial Department II, Tiergartenstrasse 17, D-69121 Heidelberg, Germany

J.P. De Greve R. Blomme H. Hensberge (Eds.)

# Stellar Atmospheres: Theory and Observations



Lectures Held at the  
Astrophysics School IX

Organized by the European Astrophysics Doctoral Network  
(EADN) in Brussels, Belgium, 10–19 September 1996



Springer

## Editors

J.P. De Greve  
Astronomy Group  
Vrije Universiteit Brussel  
Pleinlaan 2  
B-1050 Brussels, Belgium

R. Blomme  
H. Hensberge  
Royal Observatory of Belgium  
Ringlaan 3  
B-1180 Brussels, Belgium

Cataloging-in-Publication Data applied for.

## Die Deutsche Bibliothek - CIP-Einheitsaufnahme

**Stellar atmospheres** : theory and observations ; lectures held at the Astrophysics School IX in Brussels, Belgium, 10 - 19 September 1996 / J. P. DeGreve ... (ed.). Organized by the European Astrophysics Doctoral Network (EADN). - Berlin ; Heidelberg ; New York ; Barcelona ; Budapest ; Hong Kong ; London ; Milan ; Paris ; Santa Clara ; Singapore ; Tokyo : Springer, 1997  
(Lecture notes in physics ; Vol. 497)  
ISBN 3-540-63477-0

ISSN 0075-8450  
ISBN 3-540-63477-0 Springer-Verlag Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, re-use of illustrations, recitation, broadcasting, reproduction on microfilms or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution under the German Copyright Law.

© Springer-Verlag Berlin Heidelberg 1997  
Printed in Germany

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting: Camera-ready by the authors/editors  
Cover design: *design & production* GmbH, Heidelberg  
SPIN: 10643834      55/3144-543210 - Printed on acid-free paper

## Preface

Advance in science builds upon the continuous exchange of ideas, and the confrontation of theory and experiment or observation. Both should be executed by researchers with a vast knowledge of the physics and mathematics involved.

The Summer Schools of the European Astrophysical Doctoral Network aim at contributing to this in providing doctoral students in astrophysics with opportunities to enrich their knowledge in particular fields in a truly international setting. Young scientists from all over Europe (and abroad!) gather for two weeks, study and work together, and enjoy the multicultural atmosphere. Future collaboration across the border may find its roots in the lively atmospheres of the Schools.

The 1996 School dealt with the atmospheres of stars, the various theories that describe their structure and the interactions with the interior of the stars as well as with the interstellar environment, and the observations that support, modify and sometimes contradict these theories.

The School aimed at 4 goals:

- To offer an insight into problems related to stellar atmospheres for both cool and hot stars, at a high-quality level.
- To offer opportunities to deal with modern technologies in analysing observational data versus theoretical modelling.
- To learn to appreciate teamwork.
- To work and live in an international, multicultural environment.

Forty-three students attended the 1996 School, 11 females and 32 males. They came from 15 different countries. Three participants came from outside the European Union. Although a majority had a research interest in the topic of the School, Ph.D. students in all possible subdisciplines attended, their interest ranging from cosmology, over galactic structure, stellar evolution to helioseismology.

Each morning, two of the eight lecturers presented their views on one of the topics in the field. This volume contains all the lectures presented at the School. In the afternoon, practical (computer) projects with observational data were organized at the Royal Observatory of Belgium. The content of these projects was designed by the lecturers. The students learnt to work

with different astrophysical data analysis packages. To ensure multicultural cooperation the participants were thoroughly mixed in the project teams. The following projects were offered to the students: the infrared continuum and excess of hot stars (Lamers & Bjorkman), the Sobolev method with exact integration for P Cygni profiles (Fullerton), analysis of ROSAT data (Schmitt), spectrum synthesis (Hubeny). Each team of students had to choose two projects.

A cheese and wine evening, offered by the university, was organized for students and participants. The students themselves organized a dining-out evening (with a little help from the local organization), attended by practically all students and lecturers. Coffee breaks and common lunches added to familiarize us with one another.

Important parts of the program were the Show and Tell parts, which took up almost 5 hours. Students presented their own research topic and their interest in it in 5-minutes talks (with one or two transparencies), followed by a few questions.

The organization of the School is impossible without the financial help of various bodies. We take the opportunity to thank the European Commission that financed the larger part of the School, more specifically through the ERASMUS and the Human Capital and Mobility Programmes. We also thank the authorities of the Vrije Universiteit Brussel and the Royal Observatory of Belgium for their hospitality, services and financial support. The university provided favourable conditions for housing and meals. We also appreciated very much the financial support from the Swedish government and from the Fund for Scientific Research of Flanders (F.W.O.).

One of us (J.P.D.G.) heartedly thanks Vincent Icke, the organizer of the previous School in Leiden, for the valuable preliminary information on the organization. It helped me getting things on the move much easier. And the T-shirt still fits me well, Icke. Special thanks go to Tom Ray, secretary of the EADN, whose extensive advice and support definitely helped me through some tough moments, and to Koen Vyverman, whose organizational talent contributed much to the smooth and pleasant running of the School.

The enthusiasm of both lecturers and students, and the many lively discussions, made this School a truly European experience.

This publication was made possible thanks to the interest of Springer-Verlag, through Prof. W. Beiglböck.

Brussels, August 1997

Jean-Pierre De Greve

Ronny Blomme  
Herman Hensberge

# Table of Contents

## **Stellar Atmospheres Theory: An Introduction**

I. Hubeny . . . . .	1
1 Fundamental Concepts . . . . .	1
1.1 What Is a Stellar Atmosphere, and Why Do We Study It? . . . . .	1
1.2 Basic Structural Equations . . . . .	3
1.3 LTE Versus Non-LTE . . . . .	5
2 Radiative Transfer Equation . . . . .	7
2.1 Intensity of Radiation and Related Quantities . . . . .	8
2.2 Absorption and Emission Coefficient . . . . .	9
2.3 Phenomenological Derivation of the Transfer Equation . . . . .	11
2.4 Optical Depth and the Source Function . . . . .	12
2.5 Elementary Solutions . . . . .	13
2.6 Moments of the Transfer Equation . . . . .	15
2.7 Lambda Operator . . . . .	17
2.8 Diffusion Approximation . . . . .	19
3 Radiative Transfer with Constraints; Escape Probability . . . . .	20
3.1 Two-Level Atom . . . . .	20
3.2 Escape Probability . . . . .	27
4 Numerical Methods . . . . .	29
4.1 Formal Solution of the Transfer Equation . . . . .	29
4.2 Linear Coupling Problems . . . . .	32
4.3 Accelerated Lambda Iteration . . . . .	34
4.4 Non-linear Coupling Problems . . . . .	37
5 Model Atmospheres . . . . .	39
5.1 Definition and Terminology . . . . .	39
5.2 Basic Equations of Classical Stellar Atmospheres . . . . .	42
5.3 LTE-Grey Model: A Tool to Understand the Temperature Structure . . . . .	46
5.4 LTE and NLTE Model Atmospheres . . . . .	50
5.5 Line Blanketing . . . . .	52
6 Using Model Atmospheres to Analyse Observed Spectra . . . . .	57
6.1 A Scheme of Spectroscopic Diagnostics . . . . .	57
6.2 Spectrum Synthesis . . . . .	60
6.3 Spectrum Fitting . . . . .	62

6.4	Determination of Fundamental Stellar Parameters . . . . .	64
<b>Stellar Wind Theories</b>		
	Henny J.G.L.M. Lamers . . . . .	69
1	Introduction . . . . .	69
2	Basic Concepts of Wind Theories . . . . .	70
2.1	The Mass Continuity Equation . . . . .	70
2.2	The Momentum Equation . . . . .	70
2.3	The Energy Equation . . . . .	71
3	Isothermal Winds Driven by Gas Pressure . . . . .	72
3.1	The Critical Point of the Momentum Equation . . . . .	72
3.2	The Velocity Law of Isothermal Winds Driven by Gas Pressure . . . . .	75
3.3	The Density Structure of Isothermal Winds Driven by Gas Pressure . . . . .	76
3.4	The Mass Loss Rate of Isothermal Winds Driven by Gas Pressure . . . . .	77
4	Isothermal Winds with an Outward Force . . . . .	78
5	The Effect of Energy Input on a Stellar Wind . . . . .	79
6	A Wind with an $f \sim r^{-2}$ Force . . . . .	81
7	The Five Laws of Stellar Wind Theory . . . . .	83
8	Mass Loss Mechanisms . . . . .	84
8.1	Coronal Winds . . . . .	84
8.2	Dust Driven Winds . . . . .	84
8.3	Line Driven Winds . . . . .	85
8.4	Pulsation Driven Wind Theory . . . . .	85
8.5	Sound Wave Driven Winds . . . . .	85
8.6	Alfvén Wave Driven Wind Models . . . . .	86
8.7	Magnetic Rotating Winds . . . . .	87
8.8	Summary of Wind Theories . . . . .	87
<b>Cool Star Winds and Mass Loss: Theory</b>		
	Erwin Sedlmayr and Jan Martin Winters . . . . .	89
1	General Overview . . . . .	89
2	Basic Characteristics of Late-Type Stars . . . . .	91
2.1	HR Diagram Characteristics . . . . .	91
2.2	Shell Characteristics . . . . .	92
3	Self-consistent Description of Dust Forming Circumstellar Shells . . . . .	94
3.1	Chemistry of the Circumstellar Shell . . . . .	95
3.2	Dust Nucleation and Growth . . . . .	102
4	Modeling of Dust Shells Around Late-Type Giants . . . . .	111
4.1	Basic Equations . . . . .	112
4.2	External Parameters . . . . .	117
4.3	Stationary Dust Driven Winds . . . . .	118



4.4	Dynamical Models for Dust Forming Shells Around Long-Period Variables . . . . .	123
5	Conclusions . . . . .	129

### Cool Stars Winds and Mass Loss: Observations

	Thibaut Le Bertre . . . . .	133
1	Introduction . . . . .	133
2	Presentation of AGB Stars . . . . .	134
	2.1 The Evolution Towards the AGB . . . . .	134
	2.2 The Life on the AGB and Beyond . . . . .	135
3	Evidence for Mass Loss in the Optical Range . . . . .	137
	3.1 Spectroscopy . . . . .	137
	3.2 Imagery . . . . .	140
	3.3 Polarimetry . . . . .	140
4	The Infrared Range . . . . .	141
	4.1 Ground-Based Observations . . . . .	141
	4.2 IRAS . . . . .	143
5	The Radio Range . . . . .	145
	5.1 CO Emission . . . . .	146
	5.2 OH Maser Emission . . . . .	147
	5.3 Other Molecules . . . . .	148
6	Present Developments . . . . .	149
	6.1 High Spatial Resolution in the Optical and IR Range . . . . .	149
	6.2 Laboratory Studies . . . . .	150
	6.3 Space Projects . . . . .	151
	6.4 Near-Infrared Surveys . . . . .	152
7	Final Comments . . . . .	154

### The Theory of Line Driven Stellar Winds

	Henny J.G.L.M. Lamers . . . . .	159
1	Introduction . . . . .	159
2	Basic Concepts and Some Estimates . . . . .	160
	2.1 How Many Lines Are Needed to Drive a Wind? . . . . .	161
3	Radiation Pressure Due to Lines . . . . .	164
	3.1 The Radiation Pressure Due to One Line . . . . .	164
	3.2 Radiation Pressure by an Ensemble of Lines . . . . .	165
	3.3 The Lines That Drive the Winds . . . . .	167
4	The Theory of Line Driven Winds . . . . .	169
5	The Correction for the Finite Size of the Star . . . . .	173
	5.1 The Effect of the Finite Disk on the Mass Loss Rate and Velocity . . . . .	174
6	The Instability of Line Driven Winds . . . . .	177
7	Comparison Between Observations and Predictions for O and B Stars . . . . .	181

7.1	Comparison Between Observed and Predicted $v_\infty$ . . . . .	181
7.2	Comparison Between Observed and Predicted $\dot{M}$ . . . . .	182
8	Conclusion . . . . .	183

### Observations of Hot-Star Winds

A.W. Fullerton . . . . .	187	
1	Introduction . . . . .	187
2	Tracers of Stellar Winds . . . . .	189
3	Spectroscopic Diagnostics . . . . .	189
3.1	Scattering Versus $\rho^2$ Formation Processes . . . . .	192
3.2	Dissecting the P Cygni Profile . . . . .	193
3.3	Calculation of Line Profiles Formed in Stellar Winds . . . . .	198
3.4	UV Resonance Lines . . . . .	204
3.5	Optical Emission Lines . . . . .	210
3.6	Time-Dependent Structure in Hot-Star Winds . . . . .	215
4	Continuum Diagnostics . . . . .	223
4.1	Free-Free Emission . . . . .	223
4.2	Spectrum of Free-Free Emission from a Stellar Wind . . . . .	225
4.3	Mass-Loss Rates from Continuum Observations . . . . .	227
4.4	Nonthermal Radio Emission . . . . .	229
4.5	The New Frontier: Spectroscopy in the Near and Far IR . . . . .	231
5	Summary and Outlook . . . . .	232

### Circumstellar Disks

J.E. Bjorkman . . . . .	239	
1	Introduction . . . . .	239
2	Disk Diagnostics . . . . .	240
3	Theory of Circumstellar Disks . . . . .	241
3.1	Accretion Disks . . . . .	241
3.2	Outflow Disks . . . . .	250
3.3	Time-Dependent Hydrodynamics . . . . .	257
4	Radiation Transfer in Axisymmetric Systems . . . . .	260
4.1	IR Excess Emission . . . . .	262
4.2	Intrinsic Polarization . . . . .	264
4.3	Spectral Line Profiles . . . . .	270
5	Determination of Disk Geometry . . . . .	274

### Stellar Coronae

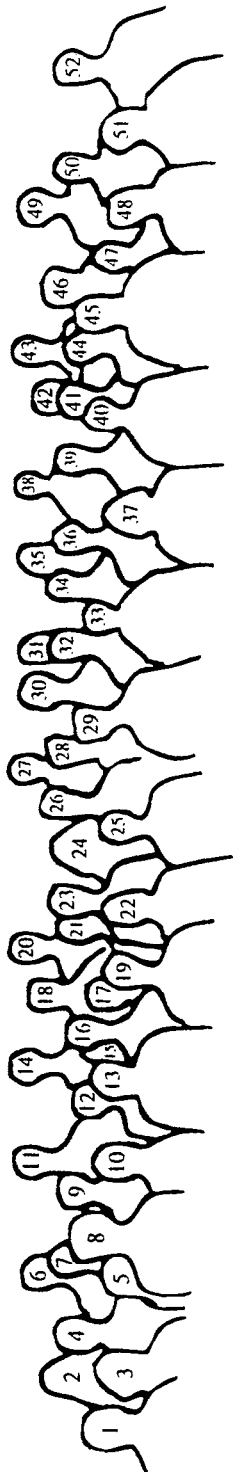
Jürgen H.M.M. Schmitt . . . . .	277	
1	Introduction . . . . .	277
2	Basic Observational Results . . . . .	282
2.1	The Solar–Stellar Connection . . . . .	282
2.2	Which Stars Have Coronae? . . . . .	283

2.3	The Sun in Perspective . . . . .	285
2.4	Rotation-Activity Connection . . . . .	285
2.5	Spectral Properties of X-Ray Coronae . . . . .	289
2.6	Physical Properties of Stellar Coronae . . . . .	291
3	Magnetically Closed Regions . . . . .	300
3.1	Magnetically Open Regions . . . . .	304
4	The Angular Momentum Problem . . . . .	309
5	Magnetized Coronal Wind . . . . .	310

**Atmospheres and Interior Models**

J.P. De Greve . . . . .	317	
1	Why? . . . . .	317
2	Recipe and Ingredients . . . . .	318
2.1	Equations . . . . .	318
2.2	Ingredients . . . . .	318
2.3	Shooting (a Solution) . . . . .	319
3	Evolution: From Wherefrom to Whereto, but Most of All: Why? . . . . .	321
3.1	Masses Make All the Difference . . . . .	321
3.2	Timescales . . . . .	322
3.3	Convection and Other Mixings . . . . .	323
3.4	Dredge-Up Phases in the Life of a Star . . . . .	326
3.5	Anchored Shell Sources (the Node Theorem for Active Shell Sources) . . . . .	327
3.6	Mass Motions of Different Shells . . . . .	329
4	Thermal Pulses or Secular Stabilities of Shell Sources . . . . .	330
4.1	Density Changes of a Nuclear Burning Zone . . . . .	330
4.2	Shell Perturbation and Pressure Change . . . . .	330
5	Cepheids (as an Answer to the Request of T. Le Bertre) . . . . .	332
5.1	The Period-Density Relation . . . . .	332
5.2	The Valve Mechanism . . . . .	333
5.3	The Kappa Mechanism (Baker and Kippenhahn 1962) . . . . .	333
6	Massive Stars ( $M > 9 M_{\odot}$ ) . . . . .	334
6.1	Mass Loss by Stellar Wind . . . . .	335
6.2	Effects on the Position in the HRD . . . . .	337
6.3	The Effect of Overshooting . . . . .	338
6.4	Internal Mixing . . . . .	338
6.5	Radius Correction for Hydrostatic Stars . . . . .	339
6.6	New Models for Massive Stars . . . . .	341

<b>Subject Index . . . . .</b>	<b>343</b>
--------------------------------	------------



- |                       |                          |                           |
|-----------------------|--------------------------|---------------------------|
| 1. Koen Daems         | 31. Jean-Pierre De Greve | 41. Jurgen Schmitt        |
| 2. Thomas Rivinius    | 32. Sven De Rijcke       | 42. Eswar Reddy           |
| 3. Goedele Ruymackers | 33. Maurizio Manfre      | 43. Neil McErlcan         |
| 4. Alex Fullerton     | 34. Jon Bjorkman         | 44. Thibaut Le Bertre     |
| 5. Gaitée Hussain     | 35. Jorge Sanz Forcada   | 45. Yves Fremat           |
| 6. Christopher Gill   | 36. Patrick Thoren       | 46. Erwin Sedlmayr        |
| 7. Bart Willems       | 37. Maria Canullo        | 47. Frau Sedlmayr         |
| 8. Alain Hui-Bon-Hoa  | 38. Ignasi Ribas         | 48. Eva Verdugo           |
| 9. Darko Jevremovic   | 39. Olivier Varenne      | 49. Alex Lobel            |
| 10. Sophie Van Eck    | 40. Jean-Claude Bouret   | 50. Stéphane Liberatore   |
|                       |                          | 51. Konstantina Manolakou |
|                       |                          | 52. Carlos Allende Prieto |

